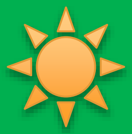
Innovative Natural-Gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-Generation
DE-FOA-0001797 (INTEGRATE)

Annual Meeting
17 September 2019
Atlanta, GA

INTEGRATE Program Objective

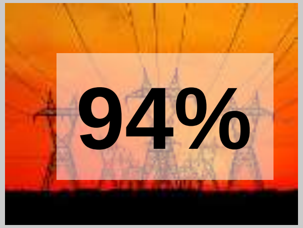
Lower the cost & emissions associated with electricity generation



Renewable

Fossil

Nuclear



Gen η	T&D η	Net η
36%	94%	34%

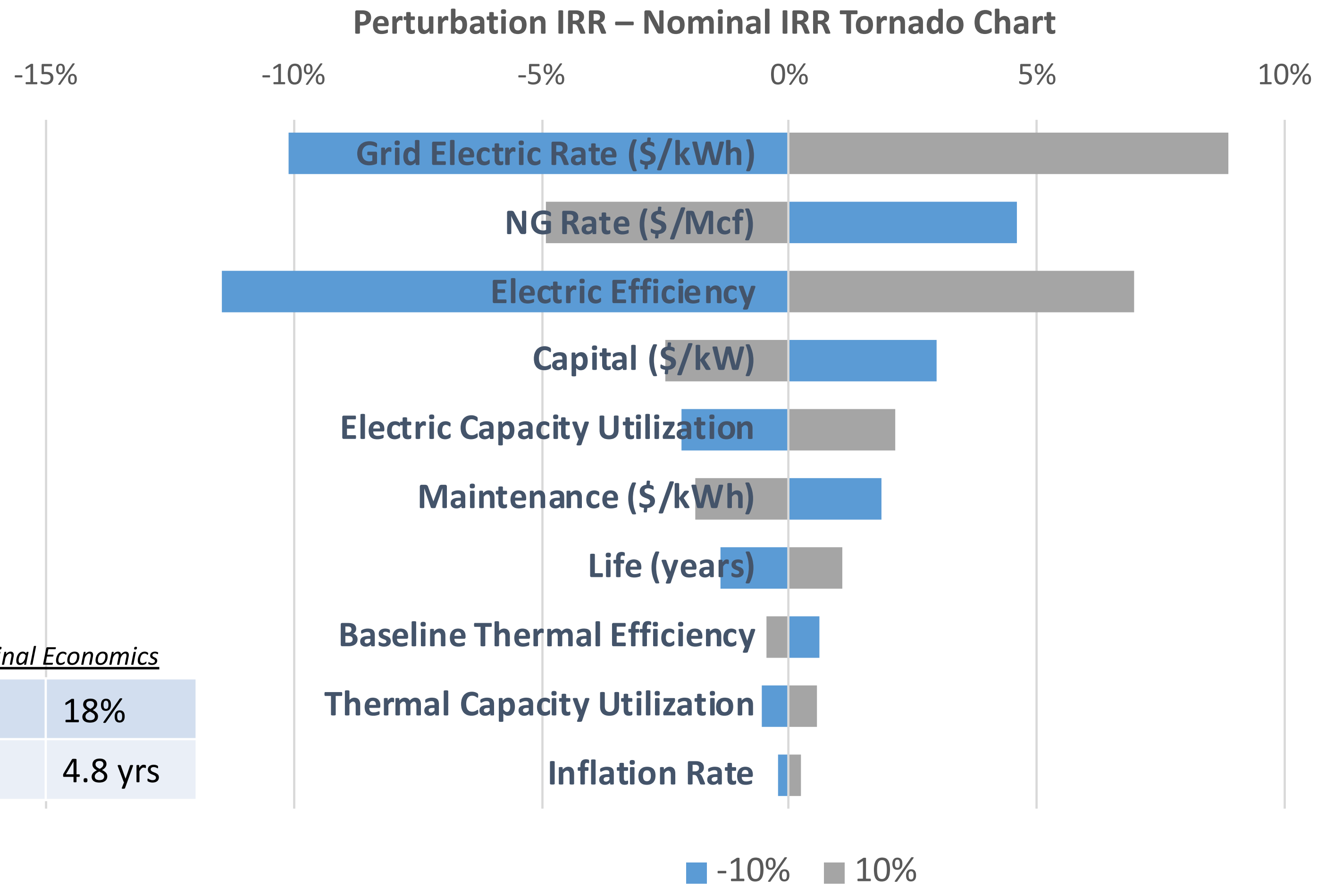
*Market requirements for 1 Quad/yr of primary energy savings for commercial electricity**

Electric Efficiency	70%
Installed Price	$1800/kW
Maintenance Cost	$0.02/kWh

arpa·e
CHANGING WHAT'S POSSIBLE

Distributed Generation Value Proposition Drivers

Economics Driven by Spark Spread, Electric Efficiency & Capital Cost



Nom
$0.10
$6.55
40%
$1000
80%
$0.02
10
90%
25%
2%

Nominal Economics

IRR	18%
PB	4.8 yrs

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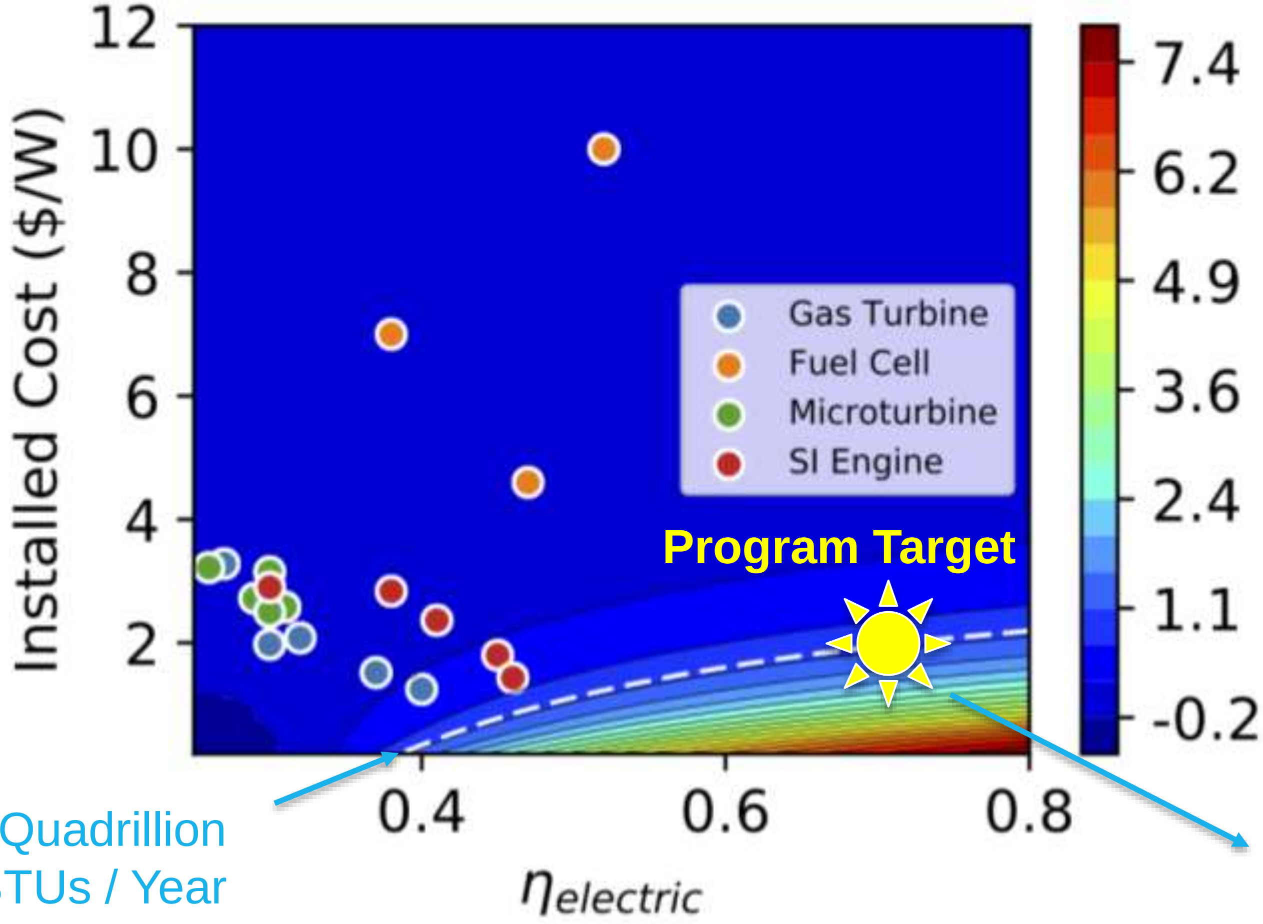
Market-Driven Performance Targets

Contours of Estimated Commercial DG Annual Primary Energy Savings (Quadrillion BTUs/Year)



1 Quadrillion BTUs / Year

$\eta_{electric}$ ≥70%, Installed Cost ≤ $1.8W

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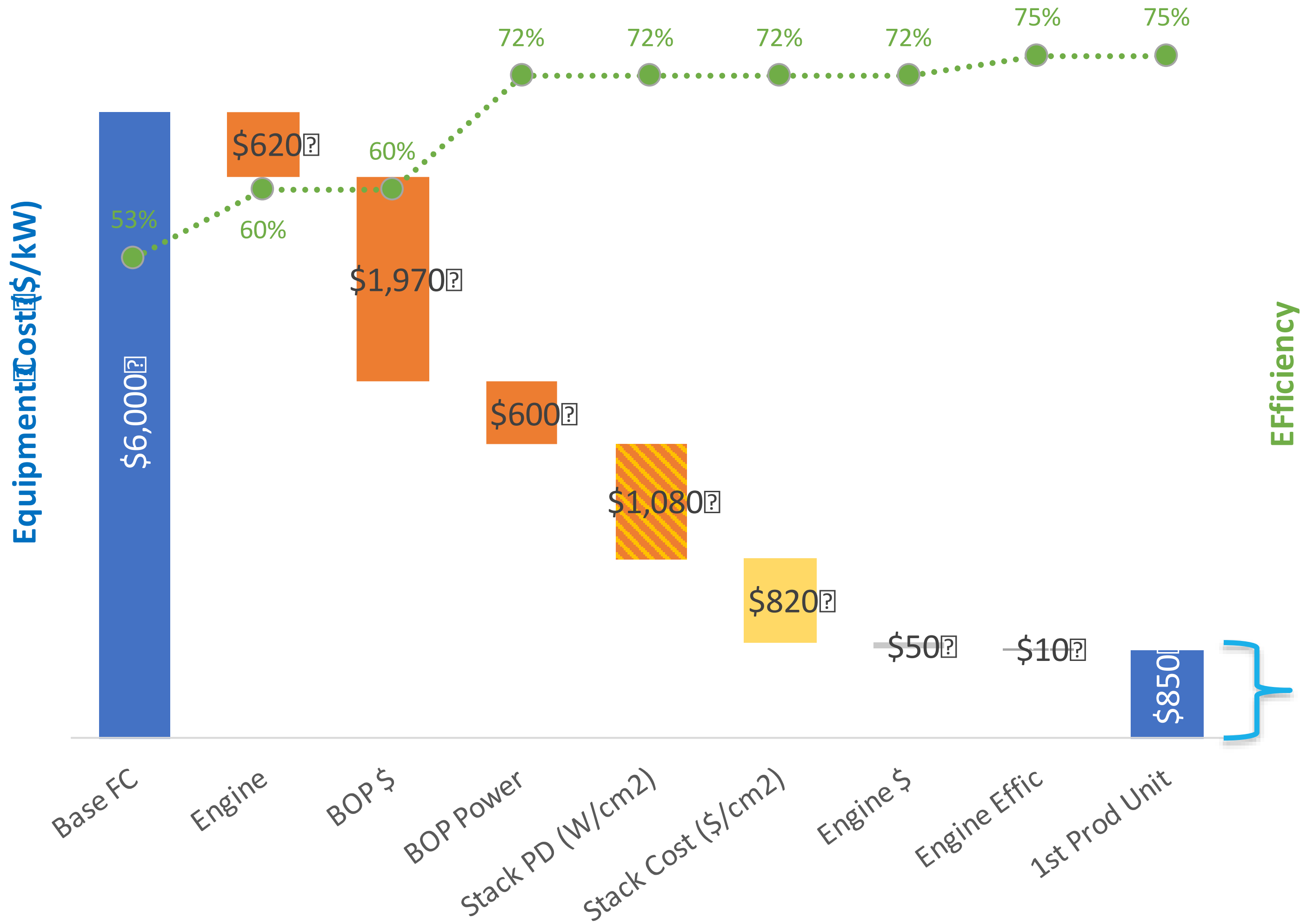
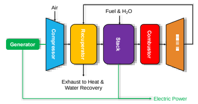
Proposed Path to Targets → Leverage Synergies





Program & Metrics

Program Structure

Phase	Focus	Max Budget
I	Enabling Technologies	\$4M
II	System Integration & Demonstration	\$10M

Technical Performance Targets

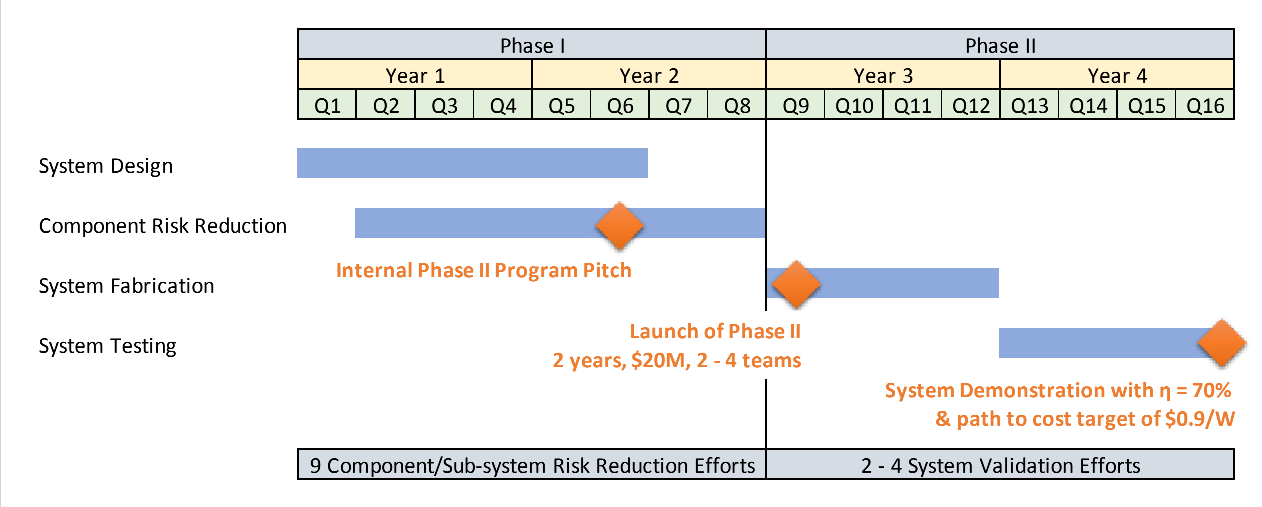
ID	Parameter	Value
1.1	Net System AC Power	≥ 100 kW
1.2	Fuel	Natural Gas
1.3	Net Fuel LHV to AC Electric Power Conversion Efficiency	≥ 70%
1.4	Full Production Equipment Manufacturing Cost	≤ \$0.9/W
1.5	System Maintenance Cost	≤ \$0.02/kWh
1.6	System availability	≥95%
1.7	System Life	≥ 20 years

General Program Strategy

<u>Staged investment plan </u>designed to <u>mitigate ARPA-E financial risk</u> by avoiding expenditures associated with the design and fabrication of complicated/expensive systems <u>until the major component & sub-system integration risks have been reduced</u>

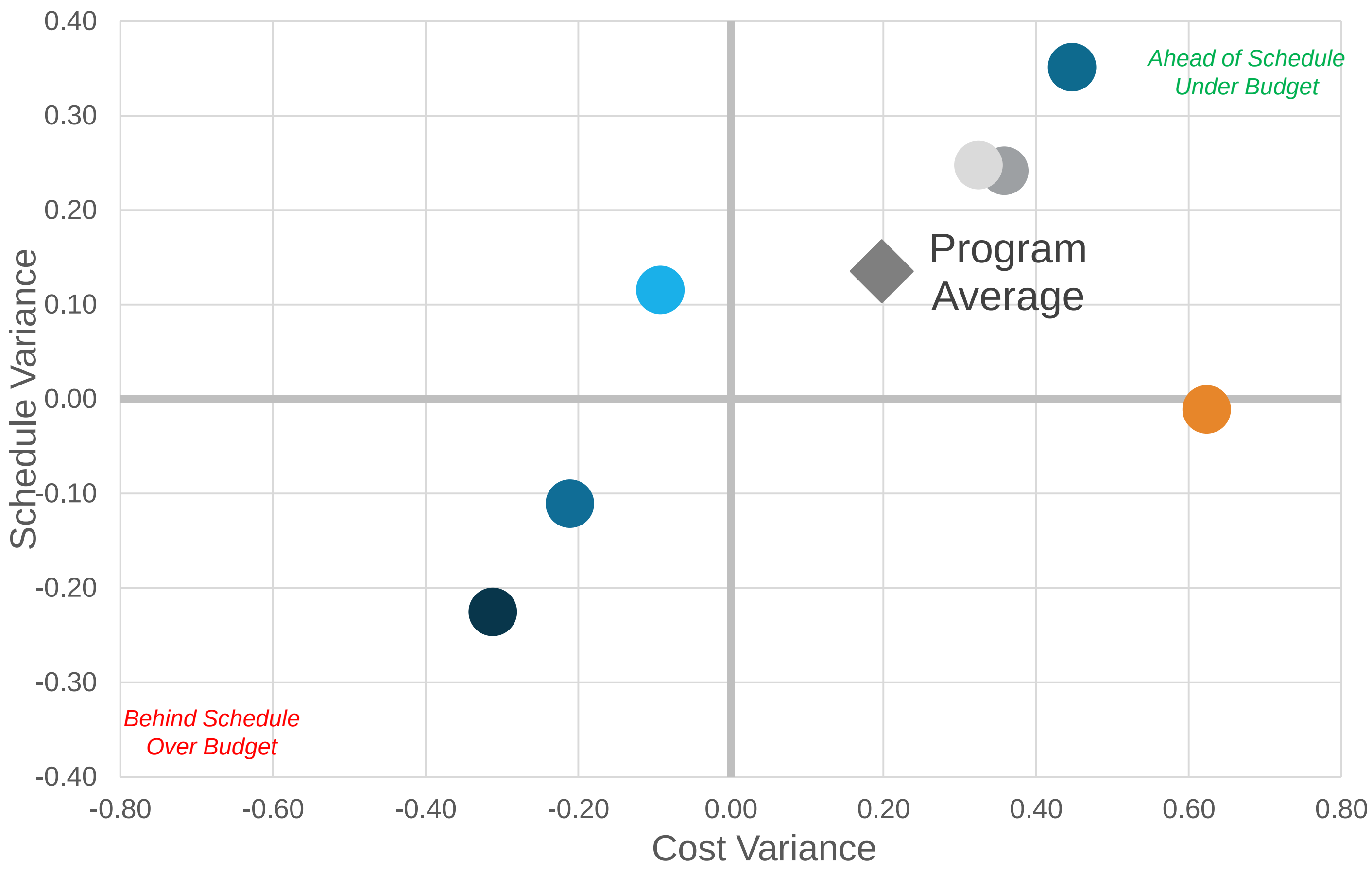
I. $20M, 2 year reduction of “component-level” risks

II. $20M, 2 year (proposed) system demonstrations



INTEGRATE Program Financial Status

3Q2019 Cost and Schedule Variance – Excludes ORNL & NETL

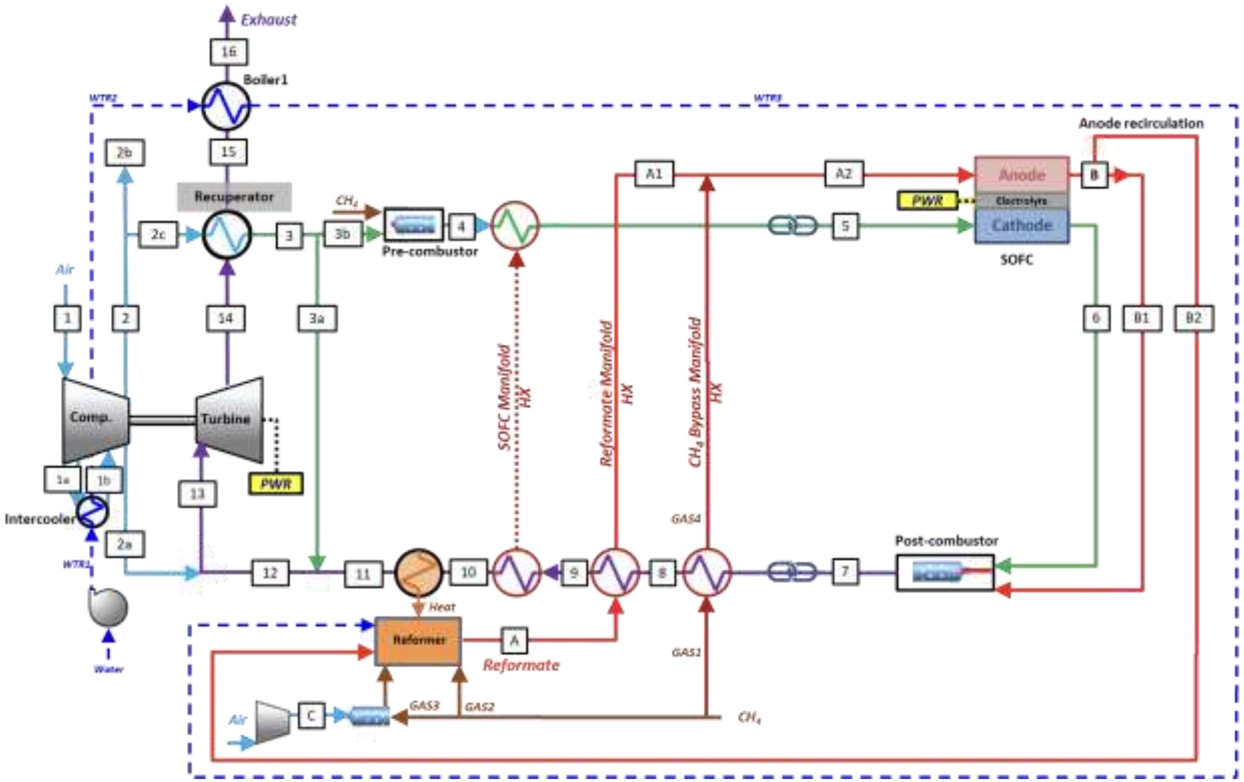


$$Cost\ Variance = \frac{(Earned\ Value\ - Actual\ Spend)}{Earned\ Value}$$

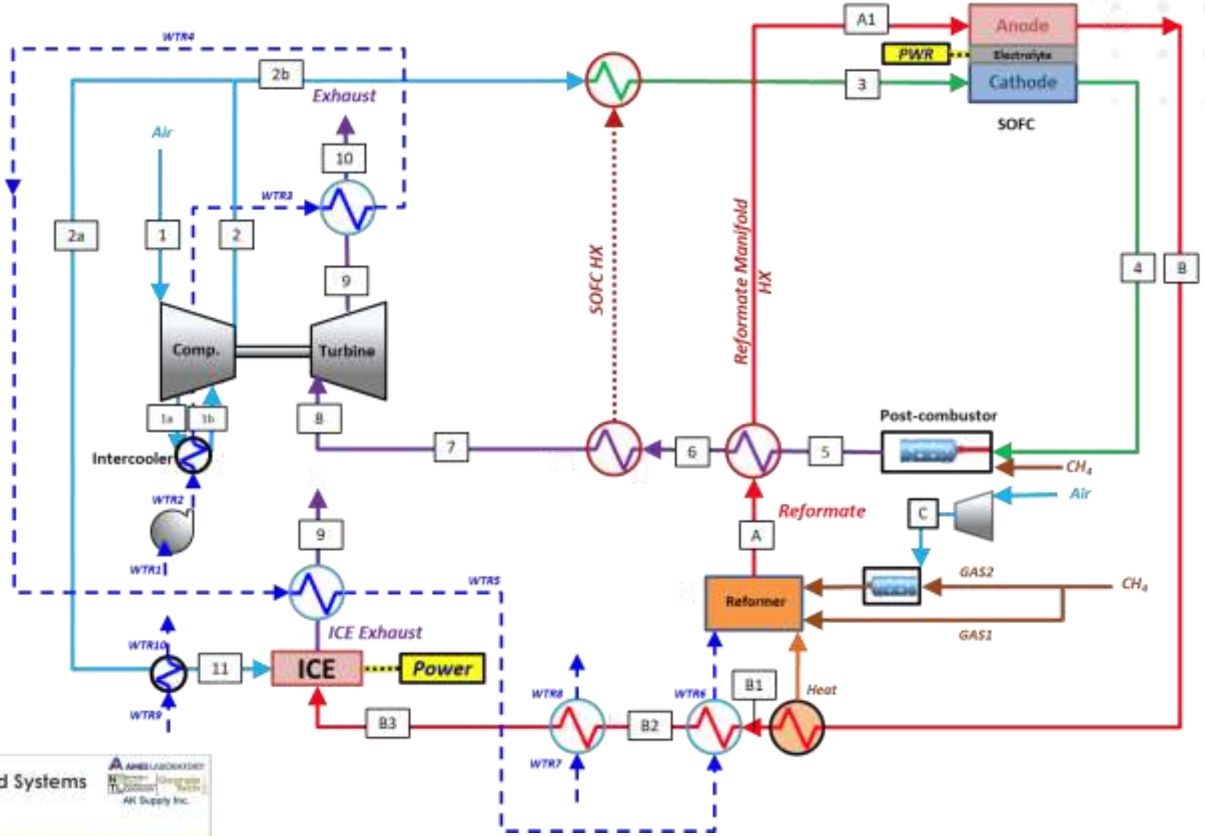
$$Schedule\ Variance = \frac{(Earned\ Value\ - Scheduled\ Spend)}{Earned\ Value}$$

Lessons Learned: Discussion Framework

SOFC → Gas Turbine



SOFC → Internal Combustion Engine
Gas Turbine



Lessons Learned: Concept Comparisons

Metric	SOFC + GT	SOFC + ICE + GT
Efficiency	$\eta_{electric}$ >70%	65 > $\eta_{electric}$ < 70%
Cost*	• Single waste exergy recovery device • High temperature materials	• Separate waste heat & fuel recovery devices • Reduced need for high temperature materials • Anode exhaust water management required • Under-utilized engine/Surge capacity

*Needs work

**Pending assessments: operability, durability, (size & weight)

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Homework Still Required (Perhaps no single conclusion)

- ***Active Issues***
  - *Thermo-<u>economic</u> Optimization*
  - ***Internal vs External Reforming***
  - *Anode Recycle*
  - *Stack Operating Pressure*
  - *Acceptable ICE water level*

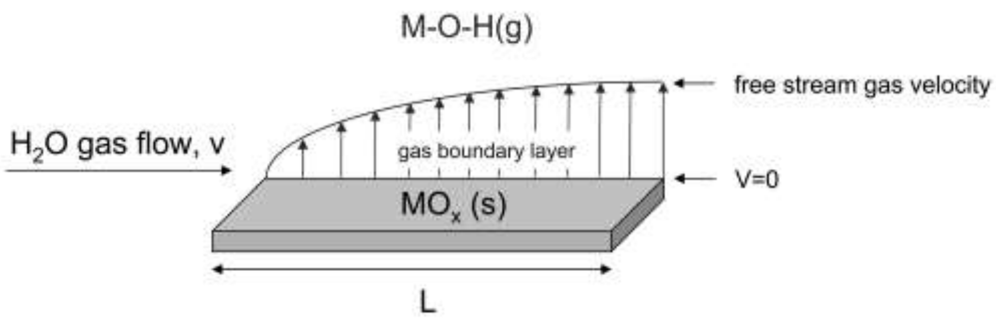
- ***Pending Issues***
  - *Operability (e.g., start-up, shut-down, load transients)*
  - *Durability (e.g. Cr poisoning)*

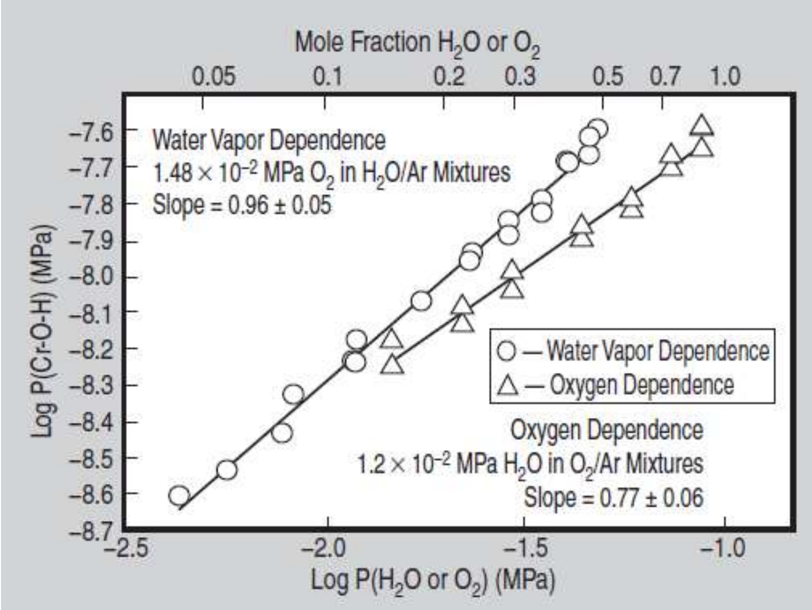
Durability Risk (1 of 2)

Increased pressure (pH_2O & pO_2) → Increased Cr poisoning risk

Mechanism #1: Moist Air

$$\tfrac{1}{2}\,Cr_2O_{3(s)} + H_2O_{(g)} + \tfrac{3}{4}O_{2(g)} \rightarrow CrO_2(OH)_{2(g)}$$





Opila, E.J., JOM, January 2006. p. 22-28.
Opila, E.J., J Phys Chem A, 2007. 111(10): p. 1971-1980.

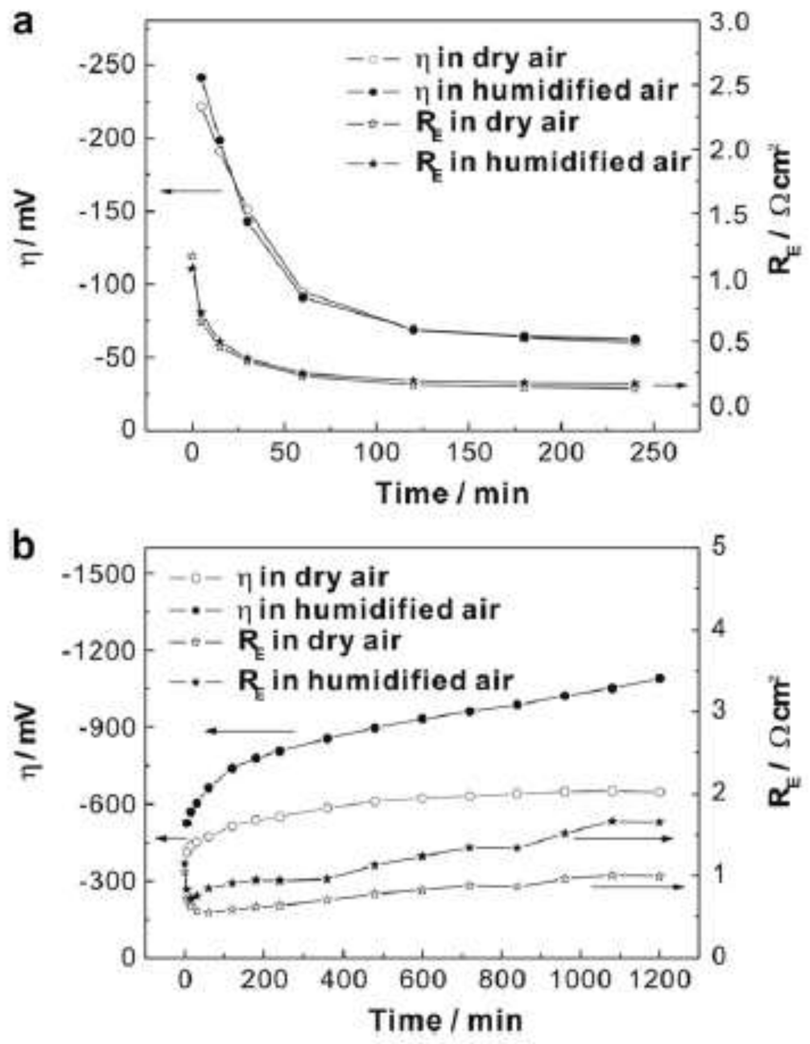
Durability Risk (2 of 2)

Increased pressure (pH_2O & pO_2) → Increased Cr poisoning risk

Mechanism #2: Dry Air/O_2

$$Cr_2O_{3(s)} + {}^{3}/_{2}O_{2(g)} \rightarrow CrO_{3(g)}$$

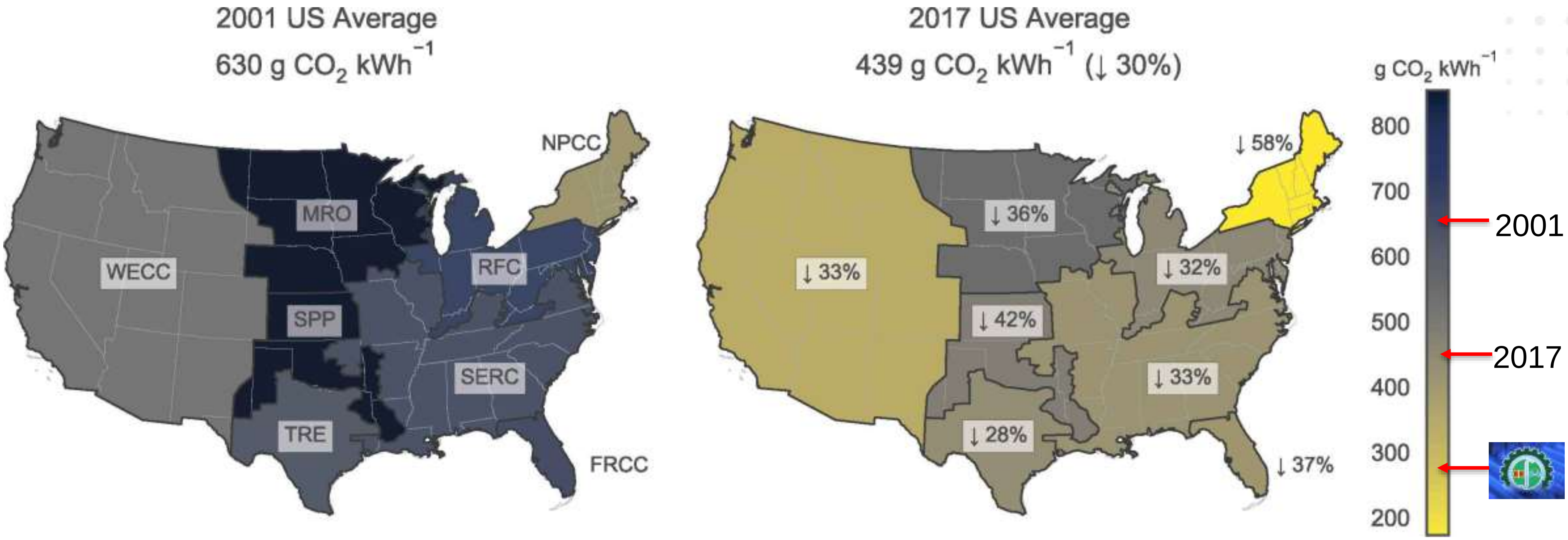
*Overpotential (left axis) and polarization resistance (right axis) for **LSM cathode** at 200 mA/cm² and **900 °C in dry and 3% H_2O air** in (a) absence and (b) presence of Fe–Cr metallic interconnect*



Please determine importance of risk in your systems & develop mitigation plans if required

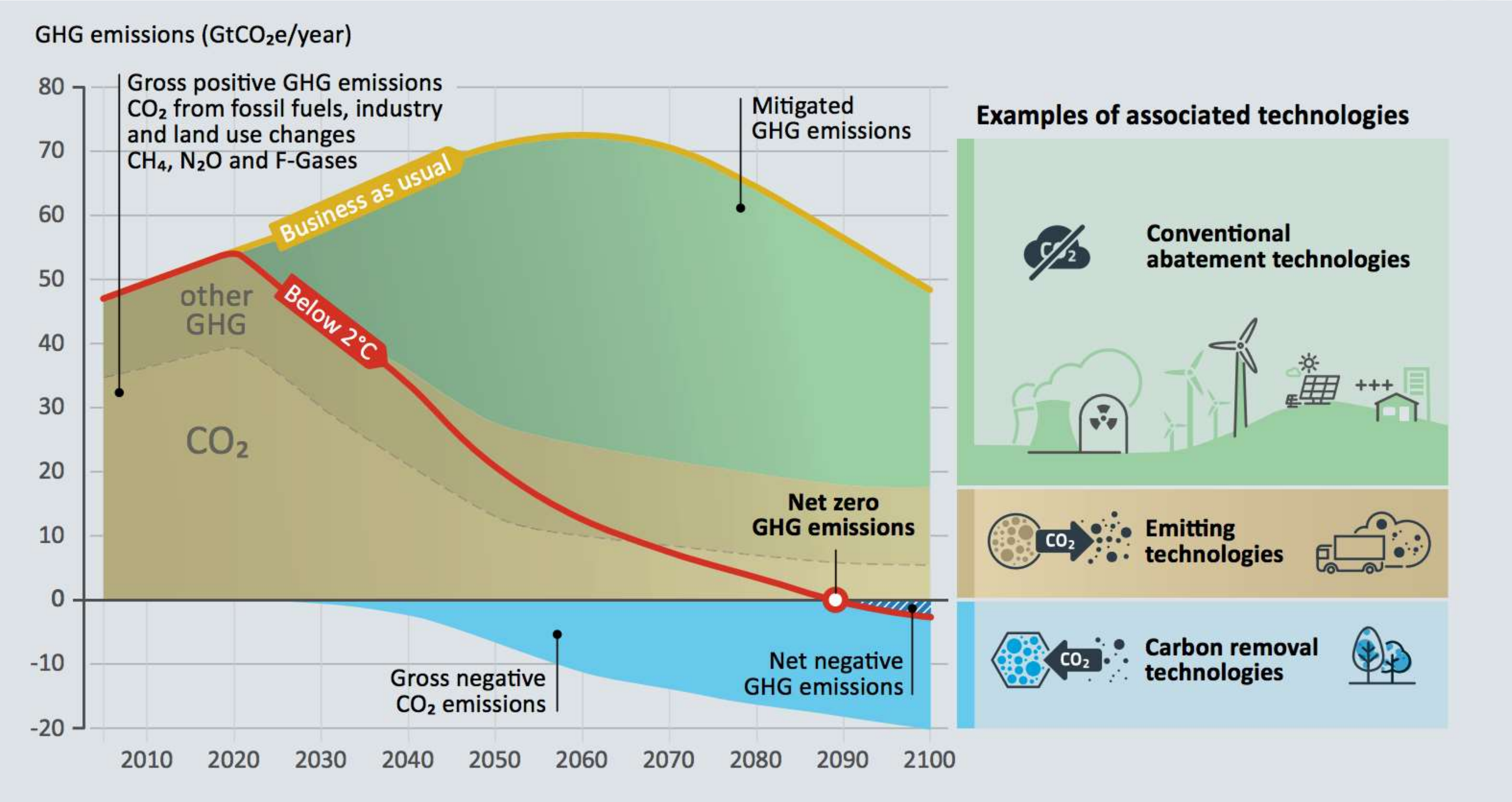
Chen, X., Int. J Hydr. Energy, 2010. **35**(6): p. 2477-2485.

US Electricity CO_2 Emissions Comparison



https://iopscience.iop.org/article/10.1088/1748-9326/aabe9d

Market Risks – Climate Pressure



National Academy of Sciences. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* 2019. p. 3

Market Opportunities

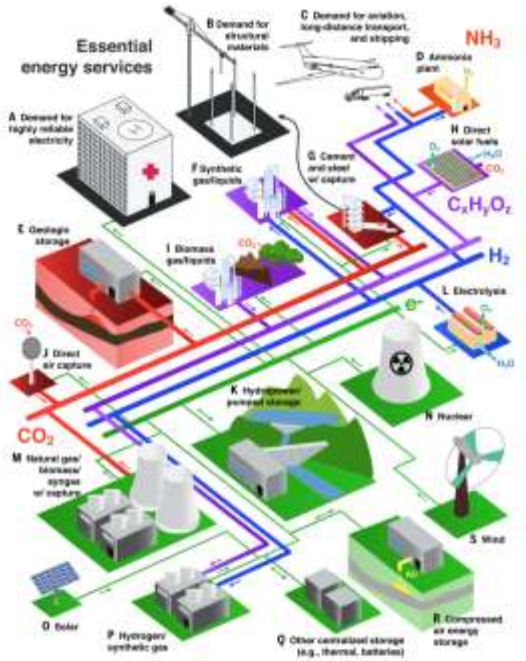
REVIEW SUMMARY

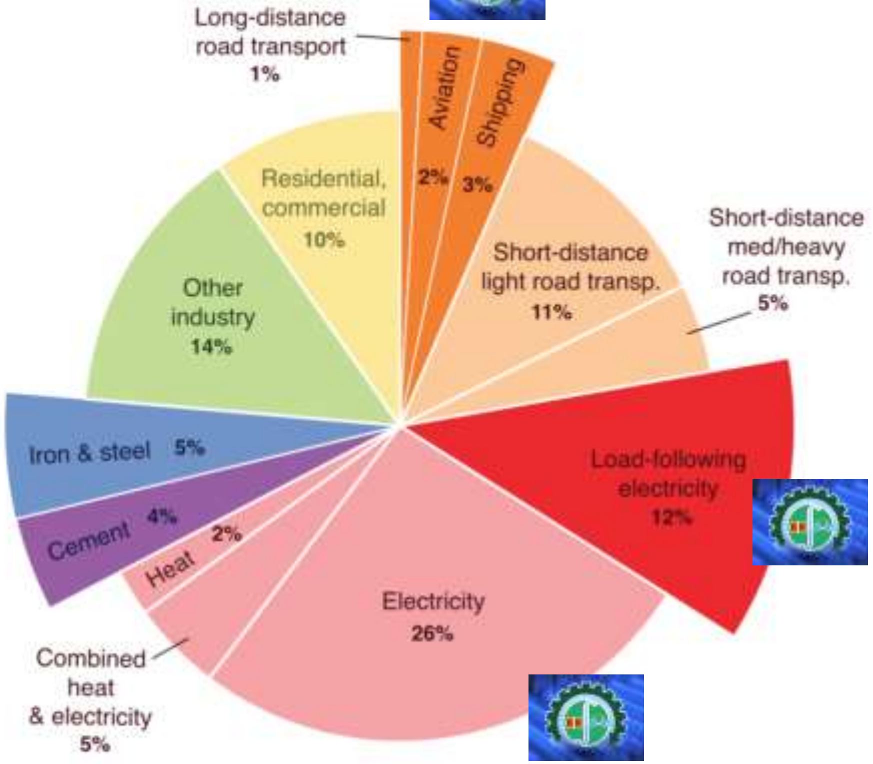
Science
June 2018

ENERGY

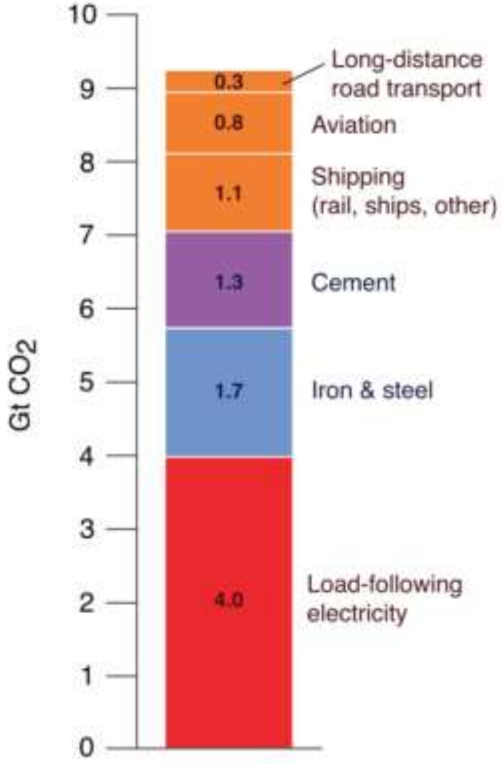
Net-zero emissions energy systems

Steven J. Davis*, Nathan S. Lewis*, Matthew Shaner, Sonia Aggarwal, Doug Arent, Inês L. Azevedo, Sally M. Benson, Thomas Bradley, Jack Brouwer, Yet-Ming Chiang, Christopher T. M. Clack, Armond Cohen, Stephen Doig, Jae Edmonds, Paul Fennell, Christopher B. Field, Bryan Hannegan, Bri-Mathias Hodge, Martin I. Hoffert, Eric Ingersoll, Paulina Jaramillo, Klaus S. Lackner, Katharine J. Mach, Michael Mastrandrea, Joan Ogden, Per F. Peterson, Daniel L. Sanchez, Daniel Sperling, Joseph Stagner, Jessika E. Trancik, Chi-Jen Yang, Ken Caldeira*





A Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)



B Difficult-to-eliminate emissions, 2014 (9.2 Gt CO_2)

Market Opportunities – Consider Faster Expansion

First Market: Commercial-Scale (100 kW → 2 MW) Distributed Generation